ECONOMICS

OF

ROAD CONSTRUCTION

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ECONOMICS OF ROAD CONSTRUCTION.

Chapter I.

HISTORICAL REVIEW.

The roads of the Romans were built at enormous cost, probably not less than $50,000 a mile. They were constructed of stone laid in mortar, the courses aggregating about 36 ins. in thickness. No regard was paid to topography. Hills were climbed or excavated, even where by a slight deflection they could have been avoided, and drainage ditches seem to have been entirely omitted. It was not until 1764 that Tresaguet, a French engineer, began to construct roads upon scientific principles by using small broken stone placed upon a well-shaped bed of larger fragments set on edge. The same type of road was later introduced into England by Telford about 1824, and roads so constructed are generally known by his name.

About the same time, or possibly a little earlier, a genius appeared in the person of Macadam, who discovered that the foundation course of large stone set on edge was unnecessary; and that, provided the soil was well drained, a bed of loose broken stone some 6 to 12 ins. in thickness would become sufficiently bound together under traffic to uphold the heaviest of wagon loads. No further advance in the science of road construction occurred until the invention of the stone-crusher and the introduction of the steam road roller, both within recent years.

It may be safely said that half the controversies between engineers over the subject of road construction are due to the fact that one class of engineers still adheres to the rules of Macadam without recognizing the changes wrought by the steam roller and the crusher. The broken stone road of to-day is quite a different structure from the type of road built by Macadam, who used hand broken stone that was practically uniform in size, laid in the road without the addition of a binder of stone dust or sand and left to be compacted by passing wheels. What was the result? The wheels cut ruts in the loose stone until the soil worked up from below, while the action of

the wheels powdered and broke some of the stone until the voids were filled, and the mass became packed, weighing 90% to 95% as much as solid stone. In this process it took 18 ins. of loose broken stone to make 12 ins. of macadam surface, or 1.5 cu. yds. of loose stone to 1 cu. yd. of macadam. To this day it is therefore stated in every text book known to the writer, that the steam roller will compress loose stone one-third, or that 6 ins. will roll to 4 ins.; which is one of the errors that seems never to be contradicted.

Rolled as roads now are with a steam roller, no such compression as this is possible; although in cases where the stone is placed upon loose unrolled earth sub-grade some stone is driven into the earth and lost, which has led many engineers to believe that the roller had compressed the stone 33%, or even more. This is mentioned as but one of the errors commonly accepted as truth, and one that is in a measure accountable for too high estimates of the amount of broken stone required on the one hand, and too low an estimate of screenings on the other hand. The true shrinkage will be given later.

With the introduction of the rock crusher came a large amount of stone dust or screenings (½-in. diameter and less). These were at first rejected as being worthless, in fact detrimental to good road construction, but some one with more brains than book-learning tried them, and found that they made the road bind more quickly and gave better results than were attained by following Macadam's specifications. The use of a binder in conjunction with the steam roller then made it possible to build a good road in a few days, where formerly it had taken months; and it led to the building of "thin roads," of 6 ins. and even 4 ins. depth of road metal. Such a radical departure from precedent was and still is ridiculed by some engineers, but common sense and economy seem now to be winning the day.

We have seen the thickness of broken stone roads reduced from the 36 ins. of the Romans to the 18 ins. of Telford, to the 12 and even the 6 ins. of Macadam, to the 6 and in some cases the 4 ins. of to-day.

The recent achievements in economic road construction are due entirely to three factors: (1) Proper drainage and rolling of the earth foundation; (2) The use of machine broken and screened stone with the screenings for a binder; (3) Thorough consolidation with a steam roller; and it is safe to say that an economic road cannot be built unless all of these factors enter into its construction. There is yet another factor that up to the present has been ignored by

engineers; namely, the use of machines for grading. Contractors have been, and are, well aware of the great economy attending the use of drag and wheel scrapers, of "road machines" and Shuart graders; but the cross section of roads designed by engineers is usually such that the use of these machines is practically impossible. A reference to the reports of the Massachusetts Highway Commission will disclose the fact that about 5,000 to 6,000 cu. yds. of earth excavation is made per mile of road, at an average cost of about 33 cts. per cu. yd.; wages being $1.50 for labor and $4.00 for team and driver for nine hours.

It can be positively stated that both the amount of excavation and its cost can be greatly reduced, and probably 50% saved, simply by a change in the cross section of the road, permitting the use of scrapers, and by a change in specifications, permitting some vegetable matter in the embankment, and the requirement of less labor in slicking, or "sandpapering," the slopes of embankments, and omission of sprinkling and rolling during construction.

This statement will become more clear upon perusal of the next chapter.

Chapter II.

EARTH ROADS AND EARTHWORK.

The cheapest in first cost and consequently the most common form of road is one made entirely of earth, properly crowned and rolled, either by wheels, or by rollers; and in any case, whatever may be the paving material, the cross section should be designed along the lines now to be described, if true economy in construction is desired.

PROFILE OF CROSS SECTION OF ROAD.—It is too prevalent a practice to design a uniform cross section for a road, regardless of the soil of which it is made; regardless of the climatic conditions, and the drainage area that the ditches must serve; regardless of the inclination or slope of ditches, and regardless of side-hill or other excavation. As an introduction to the consideration of these factors present practice in road construction will be discussed, as exemplified by the standard cross section used and recommended by the Massachusetts Highway Commission.

The ditches are commonly made 3 ft. deep, 1 ft. wide at the bottom, with side slopes of 2 to 1, as shown by Fig. 1.*

*The half-tone illustrations presented further on with explanations and comments beneath the titles, illustrate the two types of cross-section, as shown by completed macadam roads.

This great depth is given to the ditches, we are told, for the purpose of thoroughly draining the soil under the road, so that frost will not heave or destroy the road surface, a theory that the writer has not found to be sustained by experience. Even granting that a shallower ditch would leave more moisture under the road that would freeze, it becomes a very important question as to the effect of such freezing, and the writer has never seen any deleterious results in ordinary soil where the road bed had been drained by a ditch, whose bottom was 18 ins. below the crown of the road. As

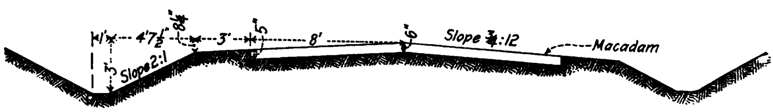

FIG. 1.—STANDARD CROSS-SECTION FOR MACADAM ROADS, MASSACHUSETTS HIGHWAY COMMISSION.

to theory, it seems probable that any expansion of the moisture in the voids of the earth upon freezing would be taken up by the 12-in. layer of dry earth between the frost and the macadam; and should it not be thus taken up, it would merely raise the whole surface of the road uniformly a fraction of an inch. It may be argued that "faulting" may be caused by the lateral pressure of frozen earth; if so, the line of weakness is in the ditch where the bulging will occur and not under the macadam; and it is erroneous to assume that expansion will take place along the axis of the road, for ice melts under pressure and flows toward the point of least resistance.

Since the writer formulated this theory to account for the fact

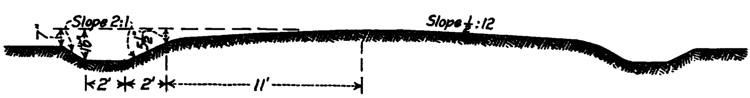

FIG. 2.—CROSS-SECTION OF ROAD WITH GENTLE CURVES AND SHALLOW DITCHES.

that freezing does not injure macadam, even where shallow ditches are used, he has received conclusive proof of its truth.

Prof. Daniel B. Luten's recent experiments upon the expansion of gravel, sand, and loam, saturated with water, and frozen in an iron tube, 36 ins. long, filled to within 3 ins. of the top, showed an expansion of $\frac{1}{2}$ in. with gravel, $\frac{1}{8}$ in. with loam, and an imperceptible amount with sand. The rest of the expansion was taken up by forcing water up through the earth, and forming a plug of ice at the top of the tube; a 1-in. ice plug on the gravel, a $\frac{1}{4}$-in. plug on the loam, and a $\frac{1}{2}$-in. plug on the sand.

Under a road, when freezing begins, the expansion, in a similar manner, will force a small amount of water up into the voids of the dry layer beneath the macadam, out into the ditches, and down into the earth below, thus causing no perceptible heaving of the macadam. It must be remembered that a soil is seldom saturated with water as in these experiments and therefore little or no expansion of the soil itself will take place under ordinary conditions. Since it is evident that deep ditches are usually unnecessary, it follows that broad shallow ditches are better, not only because less earth need be moved to form them, but because by giving the ditch a broad (24-in.) bottom, drag scrapers can be used in moving the earth. This leads to another criticism of the common design of road cross section as made by engineers who seem not to have considered the great economy attending the use of drag and wheel scrapers and road machines. Deep, narrow bottomed ditches, and the "shoulders" upon each side of the macadam, shown in Fig. 1, render the use of such machines generally impracticable. The wheel scraper is the greatest labor-saving device for moving earth short distances that was ever invented and road machines and leveling scrapers stand second only in point of merit. It can be safely said that where these machines can be used the cost of earth work will be not over two-thirds what it is where pick and shovel work is necessary. Wide, shallow ditches are favorable to the use of drag and wheel scrapers and all that remains to render the use of leveling machines possible is a gentle curving cross section profile of the finished earth surface, as shown in Fig. 2.

The cross section of the ditch shown in Fig. 2 will give sufficient earth to build the embankment forming the earth road. Here again the engineer is very likely to err, particularly if his training has been in railroad work. He will balance his cuts and fills on the longitudinal profile of the road, and entirely forget the large amount of earth that will come from the ditches. It is therefore a good rule to balance in the usual way the cuts and fills on the profile of the center, and afterward raise the grade about 3 to 6 ins. all along the road, to make room for the earth from the ditches. While Fig. 2 may be taken as a standard cross section it should be modified to suit local conditions. In very wet, soggy soil, or where the drainage area of the ditches is great, the ditches must of course be made larger; while in very sandy soil little ditching is required, for a certain amount of moisture in sand is desirable to hold it together.

LONGITUDINAL PROFILE.—Another common error made

by railroad and canal engineers is to design level or nearly level grades for long stretches of the road. In road work, however, the minimum grade should be ½% to secure longitudinal drainage of any incipient ruts that may form in the road surface; and this is especially necessary in cuts where the water seeps through and runs down the slopes of the cut, frequently washing ditches full of earth where they have only a slight grade. This leads us to the consideration of cuts.

Deep cuts form the most expensive portions of a road, both in first cost and maintenance. To reduce the first cost of earth-work

FIG. 3.—MACADAM ROAD WITH DEEP DITCHES.

(Showing a New York state macadam road of "standard cross-section" with ditches of extreme narrowness at the bottom and of unnecessary depth. Owing to not balancing cuts and fills, material has been wasted outside of ditch line and in front of fence lines.)

in cuts, the surface ditches should be narrowed until they are merely gutters.

GUTTERS AND DRAINS.—Gutters must be paved with cobblestone on grades of 2% or more. Underneath the gutter, tile drains must be placed to carry the water fed by the ditches above the cut. It should be observed that after every heavy fall of snow the mouth of all such drains and all pipe culverts must be cleaned out, otherwise water will dam back and under pressure will either overflow the road or follow along the pipe and undermine it, causing bad settlements.

Regarding the width of the road, it should never be less than 15 ft. between ditches, and preferably 22 ft. or more. The surface should not have a side slope greater than $\frac{1}{2}$-in. in 12 ins., otherwise traffic will follow the ridge in the center, and more quickly wear it out.

EMBANKMENTS.—We come now to the formation of embankments. The scissors and paste pot engineers usually specify that all material of vegetable nature must be carefully excluded from the embankments. This is unnecessary and adds immensely to the cost where the road passes through meadow land. It is of

FIG. 4.—MACADAM ROAD WITH SHALLOW DITCHES.

(Showing macadam (6 ins. x 16 ft.) road without ditches; earth shoulders 7 ft. wide; crown of road 15 ins. above bottom of earth gutter.)

course desirable to remove brush, large roots, and high weeds; but the writer has built embankments in the densely timbered and brushy country of western Washington, where no efforts were made to exclude small twigs and sod, and after eight years embankments showed no undesirable settlement. An embankment built with wheel or drag scrapers, wagons and horses, needs no rolling until its surface is shaped and ready for completion; indeed the "sectional iron roller," often specified, will produce no greater consolidation than will the wheels and hoofs. An embankment need not be made in horizontal or concave layers, as frequently required

by the engineer. All such "sandpapering" is the work of a theorist, which experience proves unnecessary.

In passing the writer will call attention to a common error, namely, that embankments shrink some 10% after construction.

Embankments made with pick and shovel and wheelbarrows do settle under the puddling action of rain, but in embankments made by teams the shrinkage takes place almost entirely during the construction, under the pounding of hoofs and wheels; and even very high embankments so constructed do not ordinarily settle over 2% afterwards. The error has probably arisen from consideration of investigations of Morris and others, showing a shrinkage of 10% when earth is taken from "cut" and put into "fill." It is true that shrinkage takes place, but the shrinkage occurs during the process of construction, not afterward.*

COST OF EARTHWORK.—The data of Morris, as copied and erroneously modified by Trautwine, are so commonly quoted as being exact enough for practical purposes, that the writer wishes here to state that not one of Trautwine's tables of costs comes within 25% to 50% of the truth for short hauls, either with carts, scrapers, or wheelbarrows. Trautwine unfortunately underestimates the cost of all earthwork except for long hauls; and there his tables are useless, since two-horse wagons, which he does not mention, are cheaper than carts. The writer will publish shortly a hand book for engineers and contractors giving all his data and conclusions in full; but for the present purpose it will suffice first to point out some of the causes of Trautwine's errors; and second to give the writer's own rules for estimating costs.

Trautwine errs, (1) in assuming that a wheel scraper or drag scraper holds the amount of earth that its catalogue size would indicate, because it will usually not go out full; and even if it does it is full of loose ploughed earth that will shrink 25% when rolled and packed by hoofs and wheels; he errs (2) in too low estimates of time lost each trip in loading and unloading; he errs (3) in the speed of horses going at a walk; they travel not 150 ft. a minute as stated by him, but 220 ft., which in a measure counterbalances some of his other errors in short hauls; he errs (4) in assuming that one driver can look after three or more carts. In Trautwine's table of costs of moving earth with drag scrapers it is stated that with leads of 40 ft. one drag scraper will move 220 cu. yds. in 10 hours, which is absolutely impossible. The writer has never seen

* For a discussion of earth shrinkage, see Engineering News, Nov. 15 and 22, Dec. 13 and 20, 1900.

more than 70 cu. yds. moved with one scraper in a day and then only in the easiest of soil and with shortest of hauls. It is high time that engineers should cease quoting such erroneous tables of costs—tables that have caused many contractors great financial loss.

The following are the writer's rules for ascertaining cost of moving earth, not including superintendence or contractor's profits, wages of laborers being 15 cts. per hour; of team and driver, 35 cts. per hour:

The length of lead is measured in feet from the center of gravity of the cut to the center of gravity of the embankment, no allowance being made for turning around at either end, as this is included in the "fixed cost."

The fixed cost includes cost of loosening, loading, dumping, spreading and lost time of men and teams, but does not include superintendence or contractor's profits and use of tools, for which at least 25% should be added. It is absurd to talk of 10% or 15% profit in earthwork, especially in a new and unknown soil.

A team can travel at a walk 25 miles in 10 hours, or at a speed of 220 ft. a minute. A laborer will load with a shovel about 15 cu. yds. (place measurement) of ploughed earth in 10 hours.

A plough, team and driver with one man holding the plough will loosen 400 cu. yds. of ordinary earth in a day; but if the hard earth crust of an old road must be loosened it will take two teams, one man riding the beam and one plough holder, to loosen about 150 cu. yds. a day.

The fixed cost of moving ordinary earth with wagons is therefore as follows:

	Cts. per cu. yd.
Ploughing	1
Loading wagon	10
Spreading	2
Time lost waiting to load and unload	5
Total fixed cost of earth in wagon	18

To this 18 cts. add 4 to 6 cts. if very tough clay or old compacted crust must be ploughed. The cost of hauling is as follows: In soft loose soils where wagons must be pulled up steep (10%) embankments, $\frac{3}{4}$ cu. yds., place measure, is an average load, while over fair earth roads with steep pull 1 cu. yd. forms a load; on hard level earth roads, $1\frac{1}{4}$ cu. yds. is a load.

Rule—To the fixed cost of 18 to 22 cts. per cu. yd. in the wagon add 0.8 cts. per 100 ft. of lead in soft roads, 0.55 cts. per cu. yd. per 100 ft. over fair roads, and 0.4 cts. per cu. yd. per 100 ft. over good earth roads.

Drag scrapers hold on an average only 0.1 cu. yd. and the fixed cost is about 10 cts. per cu. yd. of ordinary earth for leads of 100 ft. or less, to which add 6 cts. per cu. yd. per 100 ft. additional lead.

No. 1 wheel scrapers average 0.2 cu. yd. per load and the fixed

FIG. 5.—DEEP DITCH AND CULVERT PARTIALLY FILLED WITH DIRT WASHINGS.

(Showing 12-in. culvert on New York state road after nature has begun to obliterate unsightly ditches. If it is argued that so large a ditch is necessary to carry the surface water, why are culverts made of less than one-eighth the carrying capacity of the ditch?)

cost of earth in the wheeler is 10 cts. per cu. yd. for 100 ft. lead or less, to which add 3 cts. per cu. yd. for each additional 100 ft. lead.

No. 2 wheel scrapers average 0.25 cu. yd. per load, so that the cost of hauling is 2½ cts. per 100 ft.; but where a snatch team is necessary in loading 3 cts. per cu. yd. is added to the fixed cost.

To these figures for cost by scrapers or wheelers add 5 cts. if tough clay or hard road crust must be excavated.

A study of the above will disclose the fact that for short hauls no method compares in economy with the drag and wheel scrapers;

indeed earth can be moved for about two-thirds what it will cost by wagons, up to 200 ft. lead.

SURFACING.—The surface of the sub-grade should be leveled either with a Shuart grader or one of the common road machines. In cuts the ploughing should extend below the sub-grade to loosen up the earth so that the blade of the machine will more easily fill up the depressions. A grader will readily level 25,000 sq. yds. in a day at a cost of 0.02 cts. per sq. yd. If the earth road thus prepared is to be macadamized it should be thoroughly rolled with a steam

FIG. 6.—MACADAM ROAD ON STEEP GRADE, WITH SHALLOW-PAVED GUTTERS.

(Showing macadam (6 ins. × 12 ft.) road with broken stone gutters (4 ins. × 5 ft.) on 5.3% grade up which a team hauls a gross load of 12,000 lbs., exerting a tractive force of not less than 800 lbs.)

roller so that no stone will be afterward pushed down into the earth. The contractor cannot be too painstaking in this respect for his pocket-book's sake if he is to be paid for the stone by the cubic yard in place.

In loose sand the roller cannot be used at all without first covering the sand with a layer of clay or loam, or thoroughly soaking the sand with water, the latter practice often being very expensive. An inch of fine dust spread over the sand and washed in to fill the voids will be found effective and usually less expensive than the use

of cotton cheese cloth recommended by Massachusetts engineers. Half-inch to 1¼-in. screenings from the crusher may also be used to advantage; for by spreading a layer one stone thick and rolling it, no more stone will be lost in the subgrade. A thin coating of straw has also been used to hold up the macadam on a sandy soil, and other expedients will suggest themselves to the engineer not hide-bound by precedent.

We have thus far considered the itemized cost of moving earth and forming the surface. The following two examples taken from the writer's timebooks show the total cost of grading a mile of road under varying conditions. The first case shows cost of work done with wheel and drag scrapers and graders where the cross section was that of Fig. 2, designed by the writer.

Case I.—Cost of grading and surfacing one mile of road in ordinary earth, gravel and clay:

90 days, team and driver on scrapers, at..	$3.50	$315
60 days, labor on scrapers..............	1.50	90
10 days, foreman........................	2.50	25
Total, 3,000 cu. yds. excavated at.....	.14⅓	$430

In Case I. all hauls were short, none being over 500 ft., and the average not over 200 ft.; no "sandpapering" of slopes was required, but a good substantial workmanlike job throughout.

Case II.—In this case deep ditches were dug and carefully trimmed, the cross section being like Fig. 1. As the time sheet shows, there was very little teaming, but nearly all hand work. Cost of grading and surfacing one mile:

60 days, team and driver, on plough and wagon, at..........................	$3.50	$210
460 days' labor.........................	1.50	690
40 days, forman.........................	2.50	100
Total, 4,500 cu. yds. excavated at .22 1-5		$1,000

There was less hauling in Case II. than in Case I., but most of the earth was either wasted on the sides of the ditches or thrown directly into the road, and careful trimming was required, while the shoulders and general form of the cross section made it impossible to use graders.

These two cases strikingly and accurately illustrate the difference between good and bad engineering design. In Case I., using wheel

scrapers, a good road was built with 30% less excavation and at 35% less cost per cubic yard than in Case II., proving the writer's contention that road design, so far as earthwork is concerned, may be greatly improved both in Massachusetts and New York State.

The cost of earthwork and of earth roads has been discussed, not to advocate a road surfaced with earth, but because an earth road must be made upon which to build the macadam or Telford pavement. An unpaved earth road will, it is true, remain in good condition when travelled by wide-tired wagons until the fall rains begin to soak its surface, when nothing can prevent rutting first, and disintegration by frost afterward.

It is frequently stated that an earth road is as good as any other kind of road if kept well drained and free from ruts, which reminds the writer of an old saying that a certain bronze eagle in Salt Lake City "flies down to get a drink every time it hears the town clock strike." The statements are true in both cases, but the conditions are equally impossible of fulfillment.

It is not a fact that an earth road is as good as any other type, even if kept free from ruts, as the accompanying table of the number of pounds tractive force necessary to pull a ton over different surfaces clearly shows:

	Lbs.
Street car tramway	20
Asphalt	25
Stone or wood block pavement (good)	30
Macadam or plank road (good)	35
Macadam or plank road (poor)	50
Gravel, good hard road	75
Clay, good hard road	100
Earth, loose	300

It is evident that even with the best earth road only half as great a load can be hauled as on a good macadam road, which is in itself sufficient to condemn an earth road for any but a poverty stricken community.

TRACTION AND TRACTIVE POWER.—This leads naturally to a brief consideration of traction and tractive power. All authorities agree that a horse cannot exert a continuous pull of more than 100 to 150 lbs. for eight to ten hours going at a speed of 2½ miles an hour, and authorities state that for a short period of time a horse may exert double his average tractive force, or about 250 lbs.

The writer has found that a horse may exert 500 lbs. tractive force without injury for at least two hours out of ten. He has used

a team for raising a 2,000-lb. pile hammer where the power was multiplied three times by pulleys and the team has worked about three hours a day, actually lifting a weight equivalent to about 666 lbs. dead lift, which, with friction, was not less than 1,000 lbs. tractive force exerted by the team. Tests made by the U. S. Agricultural Department showed that a small pair of mules exerted a continuous pull on a trachometer of 1,000 lbs. while hauling a wagon up a steep hill. (See Fig. 6 for a view of a finished macadam road with 5.3% grade.)

It may be safely said, therefore, that a team can exert four times as much tractive energy going up a short hill as its average pull upon the level. Each added 1% of grade is equivalent to an added resistance to traction of about 20 lbs. per ton; therefore, if the average load of a wagon is 8,500 lbs. and the weight of the wagon is 1,500 lbs., the tractive force necessary to pull it over a good macadam road on the level would be 175 lbs., or over a poor macadam road, 250 lbs., which would still leave about 750 lbs. available tractive force that a team could exert going up a short hill, such a hill having a grade of 7½%. It is probable that on a smooth macadam road, and on a grade as steep as 7½%, the horses might slip and fall, so that some allowance should be made for this contingency.

It is seldom, however, that any such loads as this are hauled even over good roads, simply for the reason that there are usually stretches of poor road to be travelled by the farmer before the good road is reached; and for many years to come, certainly not within the life of macadam pavements built in the next few years, the average net load will probably not exceed three tons, which would enable a team to climb a short 8% grade without overtaxing its energies. Since it is generally a few short deep cuts that add so greatly to the cost of a road it would seem to be good engineering not to endeavor to reduce the grades where much earthwork is necessary, without careful consideration of the above stated facts. A 2% or 3% grade forms a desirable maximum if it can be cheaply obtained, since 2% or 3% is the slope of repose of a wagon on a macadam surface, and a horse can in consequence readily trot down such a grade.

Having considered the design of cross section, the cost of excavation and surfacing, and the selection of maximum grades or design of profile, let us now briefly consider the subject of the general location of the road.

LOCATION.—Upon this subject alone a volume could be written, but much already exists in print and it is not the purpose of the

writer to "re-hash" but rather to call attention to facts which hitherto have not received publication, or if published have not become generally known.

Few existing roads are well located. They are built after the style of the Romans, going over hills rather than around them. Any civil engineer would remedy such a glaring defect if given the opportunity; but there is one point in location that the engineer is almost certain to overlook if his experience has been in railroad work, namely, the character of the soil over which the road runs. Upon one side of a valley the surface may be clay, upon the opposite side gravel; in the bottom of the valley the soil is usually alluvial, higher up on a bench it is generally far more fit for road purposes. The experienced engineer will therefore not select the final location of a road until he has studied sub-surface conditions as well as topography. In locating a road in a new country the engineer will also bear in mind the fact that one of the greatest items of cost of a gravel or macadam road is the hauling of material, and will locate his road near the gravel pits or proposed quarry, wherever possible. A few culverts or drains or a few bridges will greatly swell the cost per mile of road, and these likewise the engineer will avoid if possible; and where necessary will build them as cheaply as may be, using vitrified pipe or timber for small culverts, instead of masonry arches or iron pipe; using steel I-beams with wooden floors for bridges under 30 ft. span, instead of the expensive Pony trusses so common in the eastern states. It is not unusual to see highway bridges of 60 ft. or more span over streams that never carry much driftwood or ice (the greatest destroyers of piers) where two or more 30-ft. spans resting on pile foundations would suffice, at far less expense. Bridges may frequently be avoided entirely by diverting the stream, which is a common and economic expedient in the far west.

To sum up this chapter, we find: (1) A uniform cross section for all parts of the road should not be adopted. The depth of ditches should be made to vary with the character of the soil, very shallow in sand or on steep grades and deep in flat soggy lands, but ordinarily not much more than a foot below the general ground level. The ditches should be wide enough to permit the use of drag and wheel-scrapers, and engineers should cease blindly copying plans made long before the invention of the wheel scraper and other labor-saving devices.

(2) Freezing of the soil does not destroy a macadam or other road crust, provided that there is 1 ft. of dry earth beneath the macadam.

(3) The cuts and fills should be balanced, including the earth from the ditches. No sandpapering of slopes and embankments should be specified.

(4) Select a profile with a minimum grade of ½% and a maximum grade of 3%, if it can be obtained at nominal cost; but up to 5% or even 8% if necessary to avoid expensive excavation, for the tractive power of a horse is not a constant quantity and is greater than authorities state.

(5) Design a rather flat arch for the road surface, with a total crown or drop of ½-in. in 12 ins., and avoid any shoulders or trenches in the cross section. Thus will it be possible to do the surfacing by horse instead of by man power.

(6) Locate the road with due regard to the character of underlying soil, shifting it where possible to secure better material both for sub-grade and for surfacing.

(7) Cut down the cost of all culverts and bridges as low as possible, both by careful location of the road and by economy in the design of culverts and bridges.

Chapter III.

GRAVEL ROADS.

As compared with earth roads, next in point of economy in first cost are gravel roads. As usually constructed they are but little better than earth roads for the simple reason that any gravel is considered good enough and no care is taken to screen out the poor material from the good. More than 30% of sand or loam destroys the effectiveness of gravel, rendering it pervious to water and consequently unserviceable. It may be set down as an almost infallible rule that gravel should be screened not only to exclude an excess of fines, but to insure an even distribution of fine and coarse material when placed in the road. Where a small amount of gravel is required the ordinary inclined stationary screen against which the gravel is thrown by shovel will suffice; but for extensive work it is cheaper to use a stone crushing plant with elevator, rotary screen and bins, thus breaking the very large pebbles, while by storing the gravel in bins the expense of loading with shovels into wagons is avoided and the team loses very little time in waiting to be loaded. To save cost in handling, the unscreened gravel should be shoveled into small dump cars, hauled on a track up an incline and

dumped directly over a chute feeding into the crusher. With eight men loading cars, one horse and driver hauling, one bin man and one engineer the output should be 150 cu. yds. in 10 hours of all sizes of material, part of which will probably be waste, an excess of fines being usually obtained. With labor at 15 cts. per hour the cost of screening, including coal and engineer, but not rent of plant, will be about 15 cts. per cu. yd.; since probably one-third of the output will be waste, the cost of useful product will ordinarily be about 20 cts. per cu. yd. in the wagon. The cost of hauling and rolling will be found in the following chapter, being the same as for macadam. The screen should have three sizes of circular openings, ½ in., 1½ and 2½ ins. in diameter. Considerable variation may be made from these sizes if experience with the material used gives better results.

Engineers, and especially young engineers, are prone to accept all that is published regarding "the proper sizes" and other details of construction without asking the reason why. The writer cannot too strongly urge the necessity of less empiricism and more rationalism on the part of both authors and readers. We are all too apt to believe that the particular way in which we have overcome some difficulty or solved some problem is the best and only right way, when in fact there probably are other and better methods. Even at the risk of being accused of digression the writer wishes to emphasize this contention by an example. For years it has been customary to specify that no stone in a broken stone road shall be over 2½ ins. in diameter, because it is claimed that if larger it will work to the surface. There is no doubt that if a mass of loose stone of various sizes is passed over by wheels the larger stone will tilt up when the weight comes upon one end of them and the smaller stones will roll down into the place made vacant by such tilting, and by a repetition of this process the larger stones work to the surface. But it does not follow that in a gravel or broken stone road, rolled with a steam roller and bound together with the addition of fines, a stone will work to the top if it is 2 ins. below the surface to begin with. In fact, the mass is so perfectly bound together that it is impossible for tilting to take place. In the city of Rochester, the writer has seen sections of old macadam pavements where stones 5 ins. long are to be found scattered indiscriminately through the mass, apparently just as they had been placed ten years before. Great as was Macadam, careful as were his observations, and sound as are many of his conclusions, it is evident that in this case his rule that "no stone larger than will enter a man's

mouth should go into a road," does not apply; for we use a binder where he did not; we use a steam roller where he did not; and these two factors make all the difference in the world in the behavior of the stone forming a macadam pavement. Therefore, let us not be dogmatic in naming limiting sizes of stone to be used in road construction, especially for the lower courses.

To return to the screening. The gravel passing through a 1½-in. screen will probably contain most of the softer varieties of stone, while the gravel passing through the 2½-in. screen will be of harder consistency; the smaller-sized stone should therefore form the lower layer of the road and the larger, tougher sizes the surface. It will require about one load of the screenings (less than ½-in. in diameter) to every four loads of the larger sizes to fill their voids and bind them together; and the screenings should be spread over the larger gravel, sprinkled, and rolled with a steam roller until perfectly compact, the method used being much the same as described for macadam in the next chapter. Frequently the smaller and rounded gravel cannot be rolled before the addition of the screenings, as it will push before the roller in a wave; while the top course of stone, if it has any sharp edged pieces, due to the crushing of larger fragments, may be rolled before the addition of screenings. It has been claimed by some engineers that the rounded form of the fragments of a broken cobble or large pebble make gravel unfit for road purposes, as it tends to rock under a load and so breaks the bond, rendering the road unstable. The writer does not agree with this theory, because even a poor gravel road shows no sign of instability in summer, and furthermore a stone thoroughly supported on all sides by a binder of sand or the like cannot rock.

The real cause of the failure of most gravel roads is carelessness in selection of materials and utter absence of judgment in construction, and while a gravel road will probably have to be thicker than a macadam road for equal supporting power, it remains a fact that good gravel roads have been built even without screening out the excess of fines, and still better ones can be built by following the method of preparation and construction outlined above. The writer must not be misunderstood as arguing for gravel in place of macadam. The latter is always to be preferred as a matter of ultimate economy, where good ledge rock is obtainable with a moderate haul, for, as will be shown later, the cost of quarrying is usually not to exceed 50 cts. per cu. yd., while the cost of handling and screening gravel is almost as great as the cost of crushing stone, leaving the other items of cost for both macadam and gravel prac-

tically identical, if the haul is the same. This would make a difference in cost of about 25% only, in favor of a gravel road as compared with macadam. Should good stone for macadam surfacing be expensive and no suitable quarry stone be available even for the lower course, gravel can be profitably used in place of the stone for the body of the road, which may be surfaced with 3 ins. of imported trap or other suitable rock. Telford resorted to this form of construction, but it seems not to have been mentioned in modern text books.

Chapter IV.

MACADAM ROADS.

The non-professional reader may have wondered why a mass of broken stone, when sprinkled and rolled, finally becomes a solid pavement, impervious to water, acting in all respects like concrete, although no cement mortar has been used. That such a result could be obtained seems not to have occurred to any one before the time of Tresaguet, and even he did not trust to the broken stone alone to sustain loaded wagons, for he used an underpinning or "bottoming" of large paving stone. It was Macadam who some eighty years ago, by omitting this bottoming, showed conclusively that broken stone possesses the property of knitting together or becoming cemented under the rolling action of passing wheels. The writer doubts whether Macadam himself understood the philosophy of this cementing action, and judged by the various explanations offered it is questionable whether modern engineers have fully comprehended the real cause.

WHAT HOLDS MACADAM ROADS TOGETHER?

There are those who say that the roller, by shaking and pounding the mass of loose broken stones placed on a road, finally compresses the stone together until they are almost if not quite as compact as solid rock. This they tell us is the true explanation of the binding under the roller. There are two objections to their theory: (1) The roller does not compress the stone to its original volume; that is, it does not reduce the voids to zero; (2) a road is never bound when the rolling is finished, unless a binder has been added. As a matter of fact, rolling does not reduce the voids of the mass of hard broken limestone more than one-half, leaving at least 20% voids. This the writer has determined by tests over sev-

eral miles of road where the output of the crusher was carefully measured in wagons, and afterward measured rolled in place. As corroborative evidence, the writer refers to the Transactions of the American Society of Civil Engineers, for 1899, wherein Mr. W. C. Foster states that in one instance 7.38 ins. of loose trap rock was rolled to 6 ins., while Mr. Cudworth states that in another instance 3.9 ins. was rolled to 3 ins. It is well known that the voids in loose machine broken stone are about 40%, and in order to reduce these voids to zero, 6 ins. would have to be rolled to 3.6 ins. Upon a firm foundation, where no stone can be lost in the sub-grade, and so deceive the experimenter, no one has ever rolled 6 ins. of hard broken stone to 4 ins. or reduced the voids to as low as even 6%; and common as is the false statement in text books (and New York State specifications) that this has been or can be done, the statement may be traced to one authority, namely, Macadam, who undoubtedly did see 6 ins. brought down to 4 ins., but it took months to do this under the wearing action of hoofs and wheels, which was not rolling but crushing the stone. Were any further evidence necessary to prove this contention it might be found by observing the volume of screenings or binder necessary to fill the voids in a well rolled macadam; and the amount of screenings required is never less than 20% of the volume of the rolled metal, where no screenings are wasted and the voids are completely filled. We therefore conclude that the interlocking of the fragments of stone does not account for the binding. What then does cause the binding of a macadam road? Evidently the screenings or binding materials are essential. Certain authorities tell us that the screenings have a cementing property, akin to the cementing action of quicklime or iron rust. In other words, that crystalization or setting takes place. Again the writer cannot agree with the authorities. A true explanation of the phenomenon seems to be found in a study of the sand on a sea beach.

Where the waves break, the sand is firm and makes a very fair road itself, while a little farther back, beyond the reach of the waves, the sand is loose and yielding. The waves have evidently been the means of binding the sand.

Each wave as it rushes up on to the beach carries in suspension an amount of fine sand that is precipitated upon the surface of the beach where the wave breaks and is washed down into the voids of the larger particles of sand, thus puddling or filling up all large interstices; but there is one more necessary condition to secure firmness and sustaining power, the sand must be moist. The fine

capillary pores hold the water, or rather the water in the pores holds the sand together by virtue of its surface tension, a well-known physical phenomenon, and it is this surface tension or viscosity of water that binds the sand together and makes of the sand beach an excellent surface to walk or drive over. Strange as it may seem, dust and water, commonly considered the two greatest enemies of good roads are, when in their proper places, the two elements that prevent the disintegration of macadam. The writer conceives that the authorities have been wrong in their theories and that macadam is first bound, not by a cementing action, but by the surface tension of water in the capillary voids of the screenings, and offers the following facts as evidence of the truth of this theory:

(1) A road built without screenings will not bind unless it is left long enough under the action of hoofs and wheels to produce screenings.

(2) A road built with screenings will not bind if all the dust has been taken out of the screenings, leaving only the coarser particles, but will bind immediately upon the addition of the dust and water. The writer has tried this experiment under the direction of a "good roads expert" who had ordered all the dust to be screened out, under the mistaken idea that it would be injurious to leave it in; but as stated it was found impossible to bind the road until the dust was spread over its surface and washed into the voids.

(3) A road will not bind until sprinkled, even after the screenings or binder have been added.

(4) Time for iron rust or other cementing action to take place is not necessary. A newly bound road, one that can be picked to pieces without evidence of any cementation, will uphold a heavy wagon, behaving exactly like an old road.

(5) The screenings of a very hard rock like trap bind slowly, sometimes not at all, due to insufficiency of dust necessary to produce capillary voids; but upon addition of a little sand or road sweepings bind immediately. Conversely, the screenings of a soft rock, like limestone, rich in dust bind quickly.

(6) Hygroscopic rocks (those that condense moisture upon their surface), like limestone, furnish better screenings for binding and do not ravel as quickly in dry weather as siliceous or quartzlike rocks.

(7) Long continued drought causes macadam to ravel and finally go all to pieces, while it immediately knits together again after a rain.

(8) Macadam in tunnels, where not sprinkled, soon ravels; as do likewise windswept roads that are kept free from sufficient dust and moisture.

The writer is not to be understood as advocating the use of dust and water alone to produce binding, rolling being quite as important a factor, if a road is desired that will retain a smooth surface. Rolling in the first place so consolidates the stone that there is little chance for play or movement, while the screenings and water added render appreciable movement impossible.

Sand and water, or screenings and water, though not a true mortar, serve the same purpose, as we have seen, and the less mortar in any masonry structure the more perfect and durable it is.

It may be asked what connection the dust-water theory of binding above outlined has to do with economic road construction, for good roads have been built by those to whom such a theory has never occurred, in fact by those to whom the word theory means anything entirely barren of practical results. A true theory is, however, not without economic value.

Much time has been spent and much money wasted in vain endeavor to bind trap rock without screenings or with screenings containing insufficient dust to make capillary voids. All this would have been saved had the true theory of binding been understood. Indeed, it is not uncommon to see it stated that trap rock screenings are totally unfit for binding, and they are rejected and Tomkins Cove limestone screenings or the like substituted at greater cost. The writer has found that if upon a road partially bound with trap screenings a little limestone dust or road sweepings is added the binding is immediately effected. Thus not only is unnecessary rolling in vain endeavor to bind with trap screenings avoided, but the screenings are made available at probably less cost than imported limestone, and no product of the crusher is wasted.

Where limestone screenings or dust is not to be had a little sand sprinkled over the road and washed in will serve the purpose. Another practical application of the theory in question is the following: If the surface material is brought from a long distance at considerable expense for freight and hauling, it will pay not to import the screenings also, but to use gravel and sand from some nearby pit for a binder.

Many trap rock macadam streets in Rochester have been bound with gravel, and where the rolling has been sufficient the surface remains in excellent condition, even under heavy traffic.

This expedient alone results in a saving of at least 50 cts. per cu. yd. of macadam in the matter of binding, or a saving of $800 per mile of macadam road 6 ins. thick and 16 ft. wide. It will occur to the practical man that the theory is not without economic value if by its application so large a sum can be saved per mile of road construction.

The Massachusetts Highway Commission is conducting a series of experiments to determine the cementing value of the dust of different rocks; and while the writer is not prepared to dogmatically assert that these experiments will prove entirely fruitless he thinks it probable that work is being done in a barren field. There may be some true cementing action in the crust of an old macadam road, and if so it probably aids slightly in distributing the load upon the earth foundation; but it certainly has no effect for some time after a road is built and once the cement bond is broken by the blow of hoof or wheel it cannot reform immediately, if at all. Cementation of any value is therefore secondary. We conclude that as screenings have no mysterious cementing function to perform they are, as indicated by our theory and borne out by practice, almost equally good whatsoever their composition, provided only that they are somewhat hygroscopic, but not clayey, and contain enough fine dust to form capillary voids.

QUALITY OF STONE.

Passing now to the actual construction of a macadam road, we have first to consider the kind of stone that should be selected. We find in point of durability against wear that the order followed in the accompanying table indicates the best material, the co-efficients of wear being those given in the report of the Massachusetts Highway Commission for 1899:

RELATIVE WEARING POWERS OF DIFFERENT STONE.

	Co-efficient of wear.		
Basalt (trap)	18.5	to	30.5
Diabase "	11.4	"	28.6
Sandstone	10.5	"	19
Quartzite	9.1	"	20.4
Granite	8.4	"	17.9
Syenite			12.6
Schist	11.4	"	12.2
Limestone	6.3	"	17.2
Gneiss	6.1	"	14.6
Slate			8.5
Mica Schist			4.9
Marble			2.9

These tests were made in a rattler and are therefore not entirely satisfactory, serving only in a general way to indicate what kind of rock is ordinarily the most durable when subject to attrition. The table also shows the great variability of specimens of the same class of rock coming from different sections of the country, but it is evident that despite these variations trap rock is ordinarily twice as durable as hard limestone, and four times as durable as soft limestone. It will therefore pay to surface a macadam road with crushed trap, even where it costs twice as much as limestone. Marble it will be seen is practically worthless. Atmospheric influence has a great effect upon the durability of a stone, for a rock that readily absorbs water, as does a loose grained sandstone or slate, will quickly go to pieces under the action of frost; furthermore, the cementing matrix in a sandstone is frequently quite soluable in the acidulated water that is found on a road surface. Professor Shaler considers limestone to be twice as durable as sandstone; in fact he states that sandstone and slate are quite worthless for road surface materials, lasting, as they do, not one-fifth as long as trap. Considering atmospheric agencies, as well as wear under hoofs and wheels, the rocks would stand about as follows in their proper order of value as road surface material:

(1) Trap, (2) syenite, (3) granite, (4) schist, (5) gneiss, (6) limestone, (7) quartzite, (8) sandstone, (9) slate, (10) mica schist, (11) marble.

While the order of durability above given applies to rock in the surface coat of a macadam road it must not be assumed that rocks even low down on the list are not suitable for the bottom course of a macadam road. Both in the State of New York and in Massachusetts it is common to make the lower course of local stone, surfacing it with 2 or 3 ins. of trap rock, and this is usually good practice, for the trap will outwear limestone or any of the softer rocks, several times over.

We pass now to the consideration of the form of cross section of the macadam itself. In Massachusetts and New York the standard section is about 6 ins. thick by 12 to 16 ft. wide, as shown in Fig. 1; but as above stated, the writer considers it better practice not to have the shoulders necessitated by this construction, recommending in place thereof a crescent cross-section of the macadam shown in Fig. 7. The advantages of this cross-section are obvious. The subgrade can be surfaced by road scrapers and rolled its full width, while the macadam tapering from nothing at the edges to 7 or 8 ins. at the center has the greatest thickness at the place subject to the greatest wear.

There is the additional advantage that water collecting under the macadam will quickly drain off and not be held by the shoulders. It may be objected that wheels will cut through the thin crust at the edge, but it is a fact that even 2 ins. of macadam will carry a heavy load if the sub-soil is not watersoaked, and no danger of cutting need be apprehended, since loads will come upon the edge only when teams turn out to pass one another.

QUARRYING.

Without discussing further the details of design that do not materially affect the cost of construction we shall pass to the subject of preparation of materials and cost thereof. The cost of quarrying may be divided into: (1) Cost of stripping; (2) drilling;

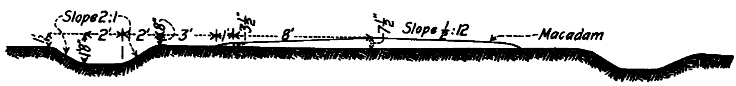

FIG. 7.—TYPICAL CROSS-SECTION OF MACADAM ROAD, AS RECOMMENDED BY THE AUTHOR.

(3) dynamite; (4) sledging large pieces and throwing them back from the quarry face.

Stripping will vary with the character of soil, depth of cut necessary and distance to which the material must be moved; the cost thereof is to be calculated as for earthwork.

DRILLING.—This should always be done with power drills. The cost of operating is about as follows per ten-hour day:

1 drill runner	$2.50
1 helper	1.50
½ engineer on boiler	1.25
⅓ ton soft coal	.75
Repairs to drill and hose	1.00
Total	$7.00

With a good drill runner, and in rock that is not very seamy, 70 ft. of hole may be drilled per day at a cost of 10 cts. per ft., but it frequently happens under adverse conditions that this cost is doubled. We shall assume 15 cts. per ft. for drilling. The number of feet of hole drilled per cubic yard of rock varies as the depth of the lift; or since the depth of hole is about the same as the depth of lift or face we shall speak hereafter in terms of the depth of hole. It is a common rule to space the holes a distance

apart equal to their depth ($s = d$); the writer, however, uses the following original formula for spacing holes in stratified rock, $s = \frac{10}{4}\sqrt{d}$.

Wherein s = distance apart and d = depth of holes.

Comparative results for various depths of holes using the formulas, $s = d$ and $s = \frac{10}{4}\sqrt{d}$:

Depth, ft. d.	Feet of drill hole per cu. yd. of rock. $s = \frac{10}{4}\sqrt{d}$.	$s = d$.
2	2.2	1.0
4	1.1	1.7
6	0.72	0.75
8	0.55	0.40
12	0.36	0.20

While the common rule ($s = d$) may be a good one in igneous rock, the writer has found that with limestone, sandstone, etc., it does not produce as satisfactory results as does his own formula. It is evident from the accompanying table that whichever rule is used the cost of quarrying increases rapidly as the depth of hole decreases; whence it is desirable to make the holes not less than 6 ft. deep, and they need not be over 12 ft. to 15 ft. deep to secure economical results.

DYNAMITE.—The amount of 40% dynamite required per cubic yard of rock excavated varies also with the depth of hole, decreasing as the depth of hole increases. In open cut work the writer uses the original formula, $P = \frac{3}{d}$, in which the P is equal to the pounds of dynamite required per cubic yard of rock.

With 40% dynamite at 15 cts. per lb. and drilling at 15 cts. per ft., we find upon summing up that the cost in cents per cubic yard of rock excavation, solid measure, using the writer's rules, is as follows:

Where d (in ft.)	1	2	3	4	6	8	10	12
Cost of dynamite per cu. yd.	26	18	15	13	11	9	8	7
Cost of drilling per cu. yd.	66	32	22	17	10	9	7	6
Total cost per cu. yd.	92	50	37	30	21	18	15	13

Having never seen a rational and detailed explanation showing that the cost of rock excavation varies inversely as the depth of the lift in the quarry, the writer has gone somewhat into detail for the purpose of demonstrating the necessity of opening up a quarry so as to secure considerable depth of face, if it is desired to move rock economically.

The formulas given are purely empirical, based upon experience, and not upon the wave theory of the effect of explosives, but it is believed that the formulas are rational in construction.

Sledging and throwing the stone back from the face will cost about 15 cts. per cu. yd., loose measure, for stratified rock where a 9 × 15-in. crusher is used. To sum up the cost of quarrying, exclusive of stripping, pumping and superintendence, we find it to be about as follows: Drilling and dynamite, 21 cts. per cu. yd. solid measure, or about 15 cts. per cu. yd. loose measure, allowance being made for waste, to which adding 15 cts. for sledging we have a total of 30 cts. per cu. yd. loose measure for quarrying.

CRUSHING.—Under this head we shall include the cost of delivering the stone from the quarry to the crusher and shall assume that a good portable crusher having a 9 × 15-in. opening is used.

The output of such a crusher is ordinarily about 60 cu. yds. in ten hours, the stone being measured loose in the bins or wagons and using a rotary screen having three sizes of circular openings, namely ½, 1¼ and 2½ ins. The output of the various sizes is about as follows: ½-in. stone, 16%; 1¼-in., 24%; 2½-in., 60%; total, 100%.

Using a stationary screen made of bars ¾ in. apart the writer has found the screenings to be about 25% of the total.

In both cases the jaws of the crusher were set to crush fine and all material over 2½ ins. in diameter was run through the crusher a second time. If the crusher is about 100 ft. distant from the face of the quarry it will take six men with wheelbarrows to supply it with stone, and it need cost no more if the crusher is somewhat further away, provided dumpcarts are used and the stone dumped on the platform. Each man will load and deliver in wheelbarrows about 10 cu. yds. of loose stone per day. It will take two active men to feed this 60 cu. yds. daily into the crusher, at a cost of 5 cts. per cu. yd. for feeding.

The engineer will receive about $2.50 a day, equivalent to about 4 cts. per cu. yd. One man will be required to help load the wagons at the bins at 2½ cts. per cu. yd., and one man to carry tools to the blacksmith, etc., will be needed at 2½ cts. a cu. yd.

A blacksmith sharpening tools at $2.50 a day, a water boy at 50

cts. and a foreman at $3.00 per day add another 10 cts. per cu. yd. to the cost of quarrying and crushing.

Summing up, we have the total cost of loose stone per cu. yd. in the wagons, with 60 cu. yds. daily output, as follows:

Quarrying and sledging	$ .30
Wheeling to platform	.15
Feeding crusher	.05
Engineer	.04
Bin man and tool man	.05
Foreman, blacksmith and waterboy	.10
⅔ ton of coal at $2.70	.03
Wear and tear on plant and interest, $3 day	.05
Total	$ .77
Delays from breakdowns	.08
Stripping, say 15 cts., and quarry rent 10 cts	.25
Grand total	$1.10

While there is no doubt that this cost may be somewhat reduced it can be done only where work is upon a sufficiently large scale to warrant the use of a stationary plant of greater size than is ordinarily used on road work, crushed stone may be bought from the large quarries at 75 cts. per cu. yd., and in certain places where the waste product of a building stone quarry is crushed it may be bought for even less.

The writer has seen many absurdly low estimates of the cost of macadam roads made by engineers who have based their prices of stone upon the prices charged by the quarrymen on the Hudson River, where work is carried on quite differently from what is possible with a portable plant and in a quarry with a shallow face.

HAULING.—Bins should always be erected to receive the broken stone and so avoid rehandling. A wagon can readily be loaded from a bin in two to five minutes. Ordinarily not more than 1½ cu. yds. can be hauled by a team. The speed of the team going and returning should average 220 ft. per minute. Allowing five minutes to dump the load and five minutes in loading, the fixed cost of hauling is 7 cts. per cu. yd., to which add ½-ct. per cu. yd. per 100 ft. of lead, or 25 cts. per mile where team and driver are worth 35 cts. per hour.

The fixed cost may readily become greater than 7 cts. if there are any delays or breakdowns at the crusher, and it is safe to say that after figuring the cost by the rule just given at least 10% should be added for such contingencies. It should be borne in mind also

that all the teams cannot be loaded at once in the morning, and furthermore that the length of haul is continually changing so that at certain times teams are not working to their full capacity.

SPREADING.—Two men will dump and spread the output of the crusher, or 30 cu. yds. each, unless the specifications compel dumping on boards and shovelling the material off therefrom into the road, under which conditions at least four men will be required. Shovelling from dumping boards is in the writer's opinion a useless and expensive refinement. It is claimed that dumping a load in one spot on the road results in undue consolidation at that place, but the writer has never seen any evidence of such an effect where

FIG. 8.—MACADAM ROAD WITH SHALLOW DITCHES, AFTER WINTER'S USE.

(Showing macadam (12 ins. x 18 ft.) road without ditches; earth shoulders, 9 ft. wide; crown of road only 15 ins. above bottom of gutter. Road in perfect condition after severe winter and wet spring.)

the spreader knows his business, and where slat bottom wagons are used, for the spreader will then not allow the load to fall all in one place, but dump in several small piles, since to do otherwise would make more work for himself. Where the output of several crushers is daily placed upon the road a Shuart grader may be used to advantage for spreading, as the blade will pick up, push along and level at least 500 cu. yds. per day, requiring a team and driver and one man at a cost of $5, or 1 ct. per cu. yd., and it will cost 1 ct. more per cu. yd. to complete the levelling by hand with a potato hook.

The screenings should not be dumped directly upon the broken stone, but placed in piles at convenient intervals along the sides of the road and spread with shovels after the rolling has been almost completed. One man will spread about 10 cu. yds. of screenings per ten-hour day at a cost of 15 cts. per cu. yd.

It should have been stated above that screening is necessary to insure the even distribution of the binder throughout the road, and Byrne errs when he advocates the placing of unscreened stone upon a road. Had he observed the way in which the larger stone in a bin roll down and collect at the lower end he would have seen the necessity of separating the sizes by means of a screen to insure even distribution.

ROLLING.—Byrne states in his work on "Highway Construction" that in England a roller averages 1,000 sq. yds. of 3-in. finished course of macadam a day, which is equivalent to 85 cu. yds. of macadam rolled; and he cites one instance where twice this amount of limestone was compacted, the roller passing over it only 35 times. If an excess of binder and water are put on before the coarse stone has been consolidated there is no doubt that macadam may be compacted in the short time above given, but the writer does not believe that a road can be properly built with so little rolling. North states that in one instance where a 6-in. course of trap macadam was applied in making repairs it took a 15-ton roller 38.2 hrs. per 1,000 sq. yds., or about 44 cu. yds. was rolled per ten-hour day. In another instance it took 58.6 hrs. to pack a 7-in. macadam, laid in two courses, or 33 cu. yds. per ten-hour day. Mr. Cudworth states that a 3-in. finished course of trap was rolled at a rate varying from 38.4 to 65.4 sq. yds. per hour, or an average of about 40 cu. yds. per ten-hour day; while Mr. Foster states that a 6-in. finished course of trap was rolled at the rate of 31.4 sq. yds. an hour, or 52 cu. yds. per ten-hour day. The writer's experience agrees very closely with that of Mr. North. For trap work, the writer has found that about 36 cu. yds. of macadam can be rolled a day and about 42 cu. yds. where limestone is used. The daily cost of operating a steam roller is about as follows:

Engineer	$ 3.00
Night watchman	1.50
4-10 ton anthracite at $5.50	2.20
Oil and waste	.30
Interest and depreciation	3.00
Total	$10.00

Interest and depreciation, as given, may seem high, but it is a common error among civil engineers not to allow sufficient for interest and depreciation of plant, because they usually forget that such a plant is not in operation continuously throughout the year. A contractor will seldom average more than 100 working days each season with his roller, therefore with interest at 6% and depreciation at 6% the total is 12% of $2,500, or $300. This must be distributed over 100 working days, and not over 300 working days, as is frequently done.

We have included no item for water, as water is usually drawn from the sprinkling tanks and is charged under that head.

With a daily cost of $10 for rolling 40 cu. yds. of macadam, which is a fair average, we have 25 cts. per cu. yd. as the cost of this item.

SPRINKLING.—Sprinkling is an extremely variable item of cost, depending upon the source of water supply and the nature of the subgrade. It will require about 4 cu. ft. of water per cu. yd. of macadam to puddle the screenings. The writer has been compelled to use as much as 18 cu. ft. of water to puddle 1 cu. yd. of macadam, but this was under the direction of an engineer who had water on the brain. One man with a good hand pump will raise 1,000 cu. ft. of water 16 ft. high in 10 hours into a tank from which it can be drawn off into the sprinklers.

If the product of two good portable crushers is going into the road it will take about 300 cu. ft. of water daily to puddle the macadam and an equal amount to keep the sub-grade in compact condition, although in very sandy soil twice as much water may be needed. One man will therefore pump enough water to supply 80 cu. yds. of macadam and sub-grade at a cost of 2 cts. per cu. yd. of macadam. A sprinkler holding 60 cu. ft. of water is ordinarily used, which at $4 per day for team, cart and driver will supply all the water needed up to a haul of 1½ miles from a storage tank. A sprinkler can be loaded in 10 minutes, and with the speed of team at 220 ft. a minute, or 2½ miles an hour, it is easy to estimate the number of trips a day and the number of sprinklers that will be needed (with varying lengths of haul). Ordinarily one sprinkler is required for each roller, so that the cost of sprinkling will be 10 cts. per cu. yd., which, added to the pumping, makes a total of 12 cts. per cu. yd. of macadam, but with a long haul and in sandy soil the cost frequently runs as high as 20 cts. per cu. yd.

QUANTITY OF MATERIALS AND COST OF WORK.—As stated above, 6 ins. of loose broken stone will compact under the roller to about 4¾ ins. in thickness, or 1.3 cu. yds. will roll to 1 cu.

yd., packed, and the voids will be reduced from about 40% to about 22%, beyond which no amount of rolling with a ten-ton steam roller will effect further consolidation. This data is based upon careful measurement of loose stone in the wagons and afterwards compacted into a macadam road several miles long. To fill the voids in the compacted stone 0.3 cu. yd. of screening (½-in. diameter down to dust) were required per cubic yard of compacted macadam.

It might seem at first sight that about 0.22 cu. yds. of screenings would be needed to fill the voids, but an excess must be provided, for the puddling action of the water used in sprinkling, and the crushing action of the roller reduces the volume of the loose screenings not less than 30%. The writer uses this rule, based upon his experience: To ascertain the thickness of the coat of screenings, multiply the thickness of the finished macadam by 0.25 and add ⅓ in. to provide for filling the surface voids and for loss. This rule will be found very accurate for any thickness of macadam from 2 to 12 ins.

To sum up: It requires the following amount of materials to make a 6-in. macadam road properly rolled and with voids* reduced to about 4%.

1.3 cu. yds. of ½ to 2½-in. loose stone,
0.3 " " " ½-in. and less screenings,

1.6 " " " total loose stone to make 1 cu. yd. macadam.

Or stated differently:

7.8 ins. of loose stone ½ to 2½ ins. in diameter will roll to 6 ins,
1.8 " " " screenings will fill the voids.

9.6 " " " stone and screenings will make 6 ins. of macadam.

The reports of the Massachusetts Highway Commission will be found to confirm this data, although their unit of measurement is the ton of 2,000 lbs., and some assumptions must be made to reduce to our unit of cubic yards. We shall assume that 1 cu. yd. of trap rock weighs 1⅓ short tons. From the report of 1897 it may be shown that 0.336 short tons of stone and screenings were required per square yard of finished macadam averaging 5½ ins. thick, or about 1.7 cu. yd. of loose stone and screenings were required per cubic yard of macadam. The report of 1899 shows that 0.328 tons were required per square yard of macadam, or 1.62 cu. yd. of loose stone and screenings per cu. yd. of macadam.

*Coddrington, in the "Encyclopedia Brittanica," states that voids in well compacted macadam are 5% as determined by actual weight.

These figures are the average of thousands of square yards of macadam road. It should be stated that in a sandy road bed or one not perfectly compacted by the roller, ½ to 1 in. of stone will be pushed into the sub-grade and lost, and if a cushion coat of screenings is specified, that also must be added to the above estimated quantities. A cushion coat is entirely unnecessary, except to prevent ravelling in dry weather, and it is then much cheaper to use sand for this purpose.

According to the present New York State specifications all the product of the crusher from ½ to 1¼ ins. in size, or 25% of the total output, is wasted, since the specifications prohibit its use. This is another of the many absurd extravagances to be found in so-called "standard specifications." While it does not produce a better road, it adds very materially to the cost of roadwork where the contractor can find no market for stone of the prohibited size.

We are now in position to estimate the cost of a cubic yard of macadam in place, and assuming the rates above given and that the full product of the crusher is used, find it to be as follows:

1.3 cu. yds. coarse stone at $1.10	$1.43
1.3 " " " " hauled 1 mile at 32 cts.	.42
1.3 " " " " spread at 5 cts.	.06
1.3 " " " " rolled at 20 cts.	.26
0.3 " " screenings at $1.10	.33
0.3 " " " hauled 1 mile at 32 cts.	.10
0.3 " " " spread at 15 cts.	.05
Sprinkling	.12
Total, per cu. yd. macadam	$2.77

This is for a haul of one mile and 40 cts. per cu. yd. of macadam must be added for each additional mile haul. As above stated, the amount of screenings will be slightly less than is necessary to bind the road, but it is assumed that a small amount of sand will be allowed to piece out; should this be prohibited by the specifications screenings will have to be imported at an additional cost.

The 1899 report of the Massachusetts Highway Commission shows that the average contract price for broken stone in place was $1.55 per ton, or about $3.40 per cu. yd. of macadam in place during 1898.

It may be well at this point to insert, for sake of comparison, the cost per mile of standard road, 15 ft. wide, 6 ins. thick at the center and 5 ins. on the sides, as constructed in the state of Massachusetts, where 175 miles of road have been built from 1894 to 1899.

The average cost has been about $10,000 per mile of road and the approximate per cent of each item is as follows:

	Per cent of total cost.
Macadam, at $1.50 ton for local stone, $2.00 ton for trap	55.0
Excavation at 32 cts. cu. yd. for earth and $1.50 for rock	14.0
Engineering	12.0
Culverts at $100 each and bridge at $1,000 each	6.0
Gravel for shoulders at 60 cts. cu. yd	5.0
Shaping or surfacing at 2 cts. sq. yd	2.0
Side drains at 29 cts. lin. ft	2.0
Stone bounds and miscl	2.0
Guard rail at 13 cts. lin. ft	1.5
Telford bottoming, at 31 cts. sq. yd	0.5
Total	100.0

The most striking fact brought out by this tabulation is that the macadam itself has cost little more than half the total, while the engineering alone has been 12% and the earthwork 14%, with sundry items forming the balance. What shall be said of such road construction? However excellent it may be in point of artistic finish and utility, a road built at such a cost indicates an extravagance that would not be tolerated by a private corporation just entering upon the construction of good roads. The item of earthwork is excessive, both as to quantity of earth moved and as to cost per cubic yard; but we shall not here repeat the criticism made in Chapter II. of the design of road cross-section that has caused so great an increase in this item.

The item of shaping, as we have shown, is likewise greatly in excess of what it would be were the use of graders possible. Culverts and bridges should ordinarily cost not half as much per mile of road as above given; while guard rails of the expensive design specified are uncalled for on a new road, and as a matter of fact guard rails are generally quite unnecessary, for while a driver might occasionally go over an embankment, were the horse possessed of no intelligence, the latter condition seldom exists.

As to the cost of engineering and inspection, we find this item to be about three times as great as it should be. The writer is an engineer and would not knowingly advise the rejection of an engineer's services on the ground of high cost. The fact is that no profession is so poorly paid, considering the brains and ability rep-

resented; but the man of wisdom will see that if roads can be built more cheaply, more roads will be built, and the engineer's services will be more in demand.

The mere survey, estimate and plans should not, and usually do not, cost over $50 per mile; while the staking out of the work need not cost over $30 per mile. It is therefore evident that inspection forms the greatest portion of the engineering item, and this is in consequence of the slow progress made by a contractor with a small and inadequate plant.

The contractor should be required to build one mile of road a month, once he has installed his crushing plant and got his quarry

FIG. 9.—ANOTHER EXAMPLE OF SHALLOW DITCHES.

(Showing macadam (6 ins. x 16 ft.) road; no ditches; earth shoulders 5 ft. wide; crown 9 ins. above gutter. Macadam perfect after severe winter and wet spring.)

stripped and ready to operate, a reasonable allowance always being made in case of bad weather. With an engineer at $5 a day and a helper at $3 a day the cost would then be about $250 per mile of road for inspection, or a total cost of $330 for survey and inspection; but since the engineer and helper cannot work continually, and yet should not be laid off or dismissed between time, it is safe to say that engineering and inspection will cost $500 per mile.

By way of comparison we shall here give the cost of a mile of road built according to Fig. 7, with all unnecessary items excluded.

3,000 cu. yds. earth excavation at $0.20	$ 600
1,500 " " macadam in place at $3.50	5,250
Culverts	300
Miscellaneous	350
Engineering and inspection	500
Total	$7,000

This price is just about two-thirds what it is costing the State of Massachusetts, but the writer is not merely theorizing, for he has constructed roads over bad country for less money than he has above named, by rigorously excluding all unnecessary items, such as stone-bounds, cast iron pipe, expensive little bridges and culverts, and by the use of rational specifications and cross sections. In regard to the cost of engineering he can also speak authoritatively, for he has laid out more than thirty miles of road himself where the engineering and inspection have together cost less than 6% of the total cost of the work.

In closing this dicussion of costs the writer should in justice state that the Massachusetts roads have been built in the worst sections of the state and in small contracts of about two-thirds of a mile in length at a time, both of which tend to increase the cost of engineering and other items. Economy in construction depends very largely upon the length of road to be built, for it costs as much to move and set up a plant to do half a mile of road building as for two miles. The fixed cost of opening a quarry and getting roads in shape over which to haul is likewise almost as great for a small piece of work as for a larger piece. To build roads economically it is therefore necessary to construct several miles at a stretch, and it is also necessary to build several hundred thousand dollars worth of roads each year in each state, for thus only can contractors afford to provide themselves with adequate plant and tools with which to do the work cheaply.

A road construction plant is more expensive than is generally known, the cost of a complete portable plant being about $7,000, distributed as follows:

1 crusher, 9 × 15 ins., with rotary screen	$1,000
Portable bins	200
1 15-HP. engine	200
1 20-HP. boiler	600
12 wheel scrapers	500
12 drag scrapers, shovels and picks	100
2 Shuart graders	100
2 steam drills	500

1 15-HP. boiler for drills	400
Water and steam pipes, quarry tools, etc	300
2 sprinkling wagons	500
1 10-ton steam roller	2,500
Total	$6,900

Due to the fact that few towns can afford such a plant, they endeavor to get along with the crusher alone, with the result that they neglect proper grading, do no rolling of sub-grade at all and waste half their stone by its becoming mixed with earth; use field stone, often rotten to begin with, because they cannot afford steam drills and quarrying plant; have a portable crusher and no bins, thereby rehandling their stone; and finally, which is the worst of all, they possess no steam roller, without which it is impossible to secure economic road construction.

So much twaddle has been published about the desirability of each township or village owning a crusher that there are scores of crushers to each steam roller in the State of New York, whereas there should be one roller to every crusher.

We pass now to a brief consideration of a type of road formerly very popular and still adapted to special conditions.

Chapter V.

TELFORD ROADS.

A Telford pavement consists of an underpinning or bottoming of large stone, usually not less than 6 ins. nor more than 12 ins. deep, set on edge like a rough block pavement and supporting a layer of macadam or broken stone.

Telford seems to be especially adapted to wet soils, not easily drained, where small broken stone would be pushed down into the soft soil, becoming mixed therewith. Wherever a cut is made, especially where the grade it flat and in a clay soil, or one of quicksand nature, it is always advisable to use the telford construction instead of macadam, for the large underpinning stone form an excellent drain and one that does not easily clog up, like pipes or side ditches, in freezing weather.

In the writer's estimation telford is far preferable to macadam, also, in city or village streets where side ditches cannot be built and where in consequence there is usually an amount of ground

water in the soil directly under the pavement sufficient in most cases to keep the sub-grade in a more or less yielding condition. In Rochester, N. Y., a telford pavement, consisting of an underpinning 10 ins. deep, of local limestone or sandstone, surfaced with 4 ins. of broken trap rock, costs about $1.25 per sq. yd., and is a pavement that is becoming deservedly popular. There are, nevertheless, many side streets where a 6-in. course of macadam alone would be about half as expensive and equally as satisfactory, where the teaming is not heavy. It has been stated in a widely read pamphlet on roads and pavements that neither macadam nor telford is an economic pavement for the streets of a village or city. The reasons cited in support of this statement are purely theoretical and based upon insufficient data to warrant so sweeping a conclusion, for not only in the city of Rochester, but in scores of other cities, are to be found most excellent examples of street pavements made of broken stone. There are, it is true, many macadam pavements that have gone to pieces under heavy traffic, but the same may be said of brick and of asphalt where improperly constructed or where poor materials have been used. The telford construction may be used to advantage where a crusher is not available, broken stone being imported for the surface coat and local stone used for the underpinning. As to the cost of a telford pavement, the underpinning will usually cost about 70 cts. per cu. yd. corded up in the quarry and will shrink in laying about 20%, bringing the cost for the stone alone to 85 cts. per cu. yd., to which must be added about 25 cts. per mile for hauling, and 25 cts. per cu. yd. for laying, making a total of $1.35 where the haul is one mile. To this add 10% for foreman and 15% for contractor's profits, giving a total of $1.70 per cu. yd. in place. Where the haul is two miles the cost will be about $2 per cu. yd., or about 33 cts. per sq. yd., for a 6-in. course of such underpinning.

The average price paid in Massachusetts in 1898 for some 10,000 sq. yds., 6 ins. thick, was 31 cts. per sq. yd. for this underpinning or bottoming. It is to be observed that a 6-in. course of underpinning can be put in just as cheaply as a 4-in. course of macadam, with a haul of two miles. A telford road is therefore not as expensive as might seem at first sight.

Chapter VI.

SUMMARY AND CONCLUSIONS.

At the close of a discussion it is always well to sum up the cardinal points brought out in the discussion in order to impress upon the mind conclusions worthy of remembrance if any there are. In the second chapter the fact was brought out that economic road construction has not been the first consideration of engineers employed by certain states, however excellent otherwise may have been the structures designed by them. It was there shown that to perform earthwork economically the engineer must understand the efficiency of modern tools that can be used and so design the cross-section of a road as to make such use possible.

We have indicated the possibility and the desirability of reducing the width of cuts by the use of sub-drain, and the necessity of keeping the mouth of such drains open after a snow.

We have shown that deep cuts may be avoided by a consideration of the fact that the power of a team is not constant but may be as great as 1,000 lbs. tractive pull for a short time, sufficient to mount a grade of 7% with a net load of four tons. We have pointed out the fact that the heaving action of frost does not materially affect a macadam road that has a foot of dry soil beneath it, and that the excessive depth of ditches so commonly seen is uncalled for.

In chapter III. attention was called to the necessity of screening all gravel that is to be used in road construction, in order to secure an even distribution of coarse and fine, as well as to exclude an excess of fines.

It was shown that large stone do not work to the surface of a gravel or a macadam road where a binder has been used, and that those who assert that such an action takes place do so entirely upon the authority of Macadam, who used no binder at all.

In Chapter IV. the endeavor was made to establish a new theory as to the cause of the binding that takes place when a broken stone road is rolled and sprinkled; and, whether the theory that water in the capillary voids of the screenings is the true binding agent shall be found to be a complete and perfect theory or not, we have at any rate shown the necessity of having fine dust in the screenings or binder.

We have indicated in detail the places where the expenses of constructing a macadam road may be legitimately reduced, beginning with less earthwork, the use of inexpensive binder, the cutting out of many expensive culverts, bridges and miscellanies and finally ending with a decided reduction in the cost of engineering.

We have suggested the construction of all roads by contract upon a scale sufficiently large to warrant outlay for a good plant; since a good road at a reasonable price has not been built by a state, town or municipality under any other than the contract system. The reason for this is that each road district or town cannot usually afford the plant necessary, and even though it could, the efficiency of men working for the public is well known to be far below the efficiency of the same men working for an individual. In Chapter V. it is pointed out that the telford construction is not as expensive as is commonly supposed, and that it is particularly adapted for cuts and in places where side ditches cannot be made, or where if made are liable to become clogged with snow.

An article upon road construction would be incomplete without some reference to the laws under which roads are built. A good State law wherein the State at large bears one-third the burden, the town or city or county directly benefited bearing also one-third, and the taxpayers along the line of the road bear the remainder, is probably the most satisfactory law under which to construct roads. Thus any farmer who owns a team and desires work can pay his share of the taxes several times over from the money he earns, securing all the benefits of the old system of working out taxes with none of the ills. The great popularity of such a law is to be found by observing its operation in New York, Massachusetts, New Jersey, Washington and other states. In New York State the new law, but two years old, has brought out petitions for over 400 miles of macadam road, which it will take four years to complete, even with an expenditure of $1,000,000 annually, while the object lesson given by the construction of these roads will result in petitions for hundreds of miles more.

A good macadam road makes its possible to reach market in all kinds of weather and at a speed before unthought of. It brings the city man into the country, and by creating a demand for property for residence purposes, greatly enhances the value of the farms. A good road makes possible the hauling of loads weighing three to five tons and it reduces the wear and tear of wagons, harnesses, horses and men.

Road construction puts money into circulation where the road

is being built, fully three-fourths of the money coming from outside sources and remaining in the road district.

No farmer with a grain of intelligence will in the face of all these facts oppose road construction under a good law; and to the credit of the shrewdness of the American farmer be it said that in no community where roads have been built as described has the verdict been anything but unanimous in favor of more good roads.